Scour protection of submarine pipelines using rubber plates underneath the pipes

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Abstract: This paper presents the results from laboratory experiments to investigate the protection of scour around submarine pipelines under unidirectional flow using a rubber plate placed underneath the pipes. The pressure difference on the two sides of the pipeline is the driving force to initiate the movement of sediment particles and can be obtained by force balance analysis. Experiments covering a wide range of incoming flow velocity, pipe diameter and plate length show that there exists a critical pressure difference over which the movement of sediment and, thus, scour takes place. Analysis of the experimental results demonstrates that this critical pressure difference is related to the pressure difference of the axial points between upstream and downstream of the pipe, which can be easily determined. This critical pressure difference is used to develop an empirical formula for estimating the critical length of the rubber plate, over which the sediment movement and scour will not take place. Good agreement between the experiments

and calculated critical plate length using the proposed formula is obtained.

Key words: Submarine pipeline; Unidirectional flow; Rubber plate; Critical pressure difference; Critical length of plate

1. Introduction

Submarine pipelines have been extensively studied in past decades due to its practical important application in offshore engineering. The stability and survivability of the submarine pipelines is among one of the focused studies. Many uncertain factors can cause the instability of the submarine pipelines. As such, the accidents of the failure and damage of the submarine pipelines have often occurred (Morelissen *et al*., 2003). One of the important factors causing such accidents is that the pipeline is suspended due to the local scour of the seabed underneath the pipe. Such local seabed scour can be greatly enhanced due to the presence of the submarine pipelines, which change the local flow pattern and increase the sediment transport capacity (Sumer *et al*., 2001a). Many studies have been carried out to investigate the mechanism of local scour (see, for example, Mao, 1986; Chiew, 1990, 1992; Sumer and Fredsøe, 1990, 2001b; Sudhan *et al*. 2002; and the excellent review paper and book by Sumer *et al*. 2001c; Sumer and Fredsøe, 2002) and the protection method of the pipeline. One of the protection approaches is to artificially bury the pipeline. However, this method will significantly increase the cost. For the pipeline laid on natural seabed, it can bury itself (the so-called self-burial (Sumer *et al*., 2001a)) under certain marine conditions as a result of the local seabed scour. Previous studies showed that such self-burial process and extent of scouring can be greatly accelerated by attaching a solid spoiler at the top of the pipe (Hulsbergen 1984, 1986; Gokce and Gunbak 1991; Chiew 1992; Bijker 2000; Cheng and Chew 2003; Li and Cheng 1999; Cheng *et al*. 2009; Yang *et al.* 2012a, b). However, the attachment of a solid spoiler also increases the disturbance intensity of the flow which in turn causes the vibration of the pipe and induces the scour downstream. In addition, successful self-burial of a pipe with or without a spoiler does require certain seabed conditions. For example, if the seabed consists of substantial clay or gravel, the self-burial of the pipeline, even with a spoiler, may not take place. Furthermore, the extent of self-burial which depends on the complex interaction of flow-soil-structure (pipelines and spoiler) could be another issue. The alternative approach for protecting the submarine pipelines is to reduce or/and prevent the scour around the pipes. Chiew (1990) investigated the prevention of the onset of the scour by placing an impermeable plate on the upstream side of the pipeline. This paper demonstrates the protection of scour around the submarine pipelines by placing a rubber plate underneath the pipe. The study shows that the presence of the rubber plate can greatly influence the scour around the pipeline. The laboratory experiments reveal that the scour depth depends on the length of the rubber plate for otherwise identical experimental conditions. A critical plate length exists over which the scour around the pipes does not take place. Such critical plate length depends on the pipe diameter, sand/soil and flow conditions, which are investigated in this study.

2. Experimental set up and procedure

The laboratory experiments were carried out in a horizontal wave and current loop which is 24.8m long, 0.5m wide and 0.6m deep. The tested pipes with a length of 0.5m were installed at two locations of the loop and they were 5.0m away from the flume bends (see Fig. 1). Sandy bed of 0.15m high and 6m long was arranged on one side of the flume and a fixed bed of the same level was on the other side. The scour profiles around the pipeline and the final scour depth were measured using a depth probe. Sixteen pressure probes were symmetrically installed around the pipe axis at the surface of the fixed bed, which were 2.7, 4.5, 6.3, 9.0, 12.2, 17.0, 22.0 and 32.5cm away from the pipe axis, respectively. The measured pressure distribution on the surface was used to calculate the pressure difference between two symmetrical points with respect to the pipe axis. Various lengths of the rubber plates with the thickness of 1mm are placed under the pipe on both the sandy and fixed beds (see Fig.2). The plates are placed above the pressure sensors on the fixed bed.

The pipe investigated here has an outer diameter (D) of 0.05m, 0.07m、0.09m, 0.10m, 0.11m and 0.13m, respectively. Several plate lengths (L=0.7D～2.3D) were used in experiments. The plate is impermeable and fixed to the bottom of the pipe. The water temperature was measured using a thermometer and kept as constant of 16^0C (the corresponding kinematic viscosity $\nu=1.118\times10^{-6}$m^2/s). Water depth is kept as constant of 0.4m for the majority of the experiments. The velocities at the different heights from the bed were measured using an Acoustic Doppler Velocimeter (ADV). The velocity measured at *0.5D* from the bed and 2 m away from the pipe (as shown in Fig.1(b)) is used as the inflow velocity (u_∞), varying from 0.24m/s to 0.50m/s. The mean diameter of sediment used in all experiments is d=0.56mm and the porosity of the sediment is kept as $n=0.4$. The experimental parameters are listed in Table 1 in which experiments in group A are used to determine the parameters in equation (7) (see below), while experiments in group B and C are used to verify the derived formula for estimating the critical length of the plate. The mechanical properties of rubber plate investigated are shown in Table 2.

3. Theoretical considerations

When the submarine pipeline is laid on the seabed without a gap and cover, currents and waves may cause local seabed scour below the pipeline. Fig. 3 is the sketch of the pipeline which is partially buried. A seepage flow underneath the pipe is generated due to the pressure difference between upstream (point *B*) and downstream (point *A*). This seepage flow increases with the increase of the current velocity and applies a hydraulic gradient force on the permeable soil particles. When the seepage flow reaches a critical value, a mixture of sediment and water will spray out from downstream of the pipeline. This process is called piping (Sumer *et al*, 2001). When the seabed scour starts, a gap between the pipeline and the bed is generated. The flow velocity in the gap can be several times greater than the velocity of the incoming flow (Jensen, 1988; Gao *et al*, 2003, 2006). Meanwhile the bed shear stress increases significantly, thereby greatly enhancing the sediment transport in the gap. This process eventually leads to the formation of a scour hole. The writers investigate this phenomenon using a theoretical analysis.

3.1 Forces acting on sediment particles

The forces acting on a small sediment particle at the seepage exit point *A* are seepage force, lift force and the submerged weight of sediment (see Fig.3). Scour will take place when the sum of the seepage force and the uplift force is equal to or greater than the submerged weight of the sediment particles. Therefore, the critical pressure difference Δp_c between points A and B, over which scour will take place, can be obtained (Sumer *et al*. 2001; Zang *et al*. 2009):

$$\Delta p_c = \frac{\rho g(S-1) - \frac{3}{4} C_L \frac{\rho {u_b}^2}{d}}{\lambda_A} \alpha D \tag{1}$$

where λ_A = a calibration coefficient, α = the angle defined in Fig.3 with the value of 0.22 radian in this study, u_b = the water velocity on the seabed, C_L = the coefficient of uplift force, ρ = the specific weight of water, S = the specific gravity of sediment particles ($S=\rho_s/\rho$); ρ_s = the specific weight of sediment particles; g = the gravitational acceleration. For the flow velocity being at the *0.35d* height above the bed, C_L can be chosen as a constant of 0.178 (Chien and Wan, 1999).

The laboratory experiments (Yang *et al*. 2012) showed that there exists a relationship between the pressure difference of points A and B and pressure difference of points A' and B'. Therefore, the critical pressure difference for the onset of the scour can be obtained by investigating the pressure distribution around the pipeline.

3.2 The pressure on the surface of the pipeline

Assume that flow separates from the cylinder at $y=y_s$ (see Fig. 3), the pressure distribution behind the separation point of the boundary layer in the lee side can be expressed as (Ren *et al*. 2010):

$$p(y) = p_1 + \frac{1}{2}\rho u_\infty^2 m + 2\rho u_\infty^2 \mu^2 \left(\pi - \frac{y}{R_0}\right)^2 - \frac{2}{3}\rho u_\infty^2 \mu^4 \left(\pi - \frac{y}{R_0}\right)^4 \tag{2}$$

where $y \geq y_s$; p_1 = the reference pressure at a point of the undisturbed upstream; R_0 = radius of the pipe; μ = correction coefficient; m = coefficient related to the flow Reynolds number. For the problem under investigation, we are only interested in the pressure at point *A'* where $y=\pi R_0$. Therefore, the pressure at *A'* can be estimated by substituting $y=\pi R_0$ into (2):

$$p_{A'} = \frac{1}{2} m \rho u_\infty^2 + p_1 \tag{3}$$

The pressure at point *B'* can be obtained by applying the Bernoulli equation along a streamline between *B'* and an undisturbed upstream point of the same height. The pressure difference between *B'* and *A'* can then be evaluated as:

$$\Delta p_{B'A'} = \frac{1}{2}(1-m)\rho u_\infty{}^2 \tag{4}$$

The maximum pressure difference between two points on the bed takes place at points *A* and *B*. As aforementioned, this maximum pressure difference is related to $\Delta P_{B'A'}$, thus, can be estimated as following:

$$\Delta p_{\max} = \Delta p_{AB} = \lambda \frac{(1-m)\rho u_\infty^2}{2} \tag{5}$$

where λ = a calibration coefficient. Detailed analysis of the authors' experimental data reveals that, for the cases without a plate underneath the pipe, the variation of the pressure difference between upstream and downstream along bed with the distance is an exponential distribution, which can be expressed as:

$$\Delta p = \Delta p_{\max} e^{k(\sin\frac{\alpha}{2} - \frac{X}{D})} \qquad X \geq D\sin\frac{\alpha}{2} \tag{6}$$

where k = a correction coefficient; X = the horizontal distance between two symmetrical points with respect to the axis of the pipe.

3.3 The critical length of the rubber plate

The motivation of this study is to investigate the protection of the scour around the pipelines using a plate placed underneath the pipe. The experiments reveal that the pressure difference between upstream and downstream of the pipe for the case with a plate placed underneath the pipe is smaller than that of the case without a plate for otherwise the identical conditions. The affected region on bed is the length of plate and there is little change for the pressure beyond the covered area (see Fig.4). For the cases in which the length is shorter than a certain value, the sediment transport will start at the downstream edge of the rubber plate. When the rubber plate length reaches a certain value for a given input condition, there is no sediment transport and no scour takes place around the pipeline. This means that there exists a critical length of the plate which can prevent the pipeline from scouring. When the length of the plate is equal to or greater than this critical value, the maximum pressure difference between upstream and downstream of the pipe is less than or equal to the critical pressure difference over which the scour will take place. This condition can be expressed as:

$$\Delta p \le \Delta p_c \tag{7}$$

Substituting (1), (5) and (6) into (7) yields the critical length of the plate L_{cr}:

$$L_{cr} = D\{\sin\frac{\alpha}{2} - \frac{1}{k}\ln[\frac{2g(S-1)-\frac{3}{2}C_L\frac{{u_b}^2}{d}}{\lambda_A\lambda(1-m){u_\infty}^2}\alpha D]\} \tag{8}$$

Parameters in (8) are determined using the experiments in group A in Table 1 and previous studies of the authors (Yang *et al*. 2010). The proposed formula will then be verified using the experimental data in group B and C in Table 1.

4. Results and discussion

The sediment transport and scour depth around the pipe with and without a plate underneath the pipe are observed and measured for various experimental conditions. The experiments reveal that the sediment transport and scour depth around the pipe can be significantly reduced when a rubber plate is placed underneath the pipe, indicating that a plate can effectively protect the scour around the pipeline.

4.1 Pressure distribution along the bed

In order to examine the effect of the rubber plate on the prevention of sediment transport and scour around the pipeline, the hydrodynamic pressure distribution along the bed is measured for a range of input conditions. The experimental measurements for various flow and structure parameters reveal that the pressure distribution has similar tendency. Fig. 4 is an example for u_∞=0.24m/s and D=9cm without and with a plate (length=1.0D and $2.0D$). It is seen that the hydrodynamic pressure is positive upstream and negative downstream for both the cases with and without a plate. Fig.4 clearly shows that the presence of the plate reduces the pressure on bed and such pressure reduction increases with the increase of the plate length.

It is noted from Fig. 4 that the maximum positive and the minimum negative pressure takes place at the contact points of upstream and downstream respectively. The absolute values of the hydrodynamic pressure on the bed decrease with the distance from the pipe axis and approach zero at the sufficiently large distance.

It is well known that the pressure difference between upstream and downstream of the pipe is the main driving force for the onset of the scour. For a given condition of flow, sediment and pipe, the scour is controlled by the pressure difference. The depth of the scour increases with the increase of the pressure difference. When the pressure difference is equal to or smaller than a critical value for the onset of the sediment movement, the scour will stop. The experimental results demonstrate that the pressure difference can be reduced by placing a rubber plate under the pipe. As the pressure difference decreases with the presence of the plate, the scour depth around the pipe is reduced. The effect of the plate length on the scour depth is investigated and compared with that without a plate for otherwise the identical conditions. Fig. 5 is the plot showing the variation of the relative scour depth h_f/h_0 (h_0 = the scour depth without a plate; h_f = the scour depth with a rubber plate for otherwise identical conditions) with the dimensionless plate length (normalized by the pipe diameter) for three incoming flow velocities. It is seen that for given flow conditions, the depth of the scour hole significantly decreases with the increase of the plate length. For given flow conditions, there is a critical length of the plate over which there is no sediment transport and scour taking place at all. This critical length of the plate can be estimated by equation (8) whose coefficients are determined as following.

4.2 Determination of Coefficients

4.2.1 Calibration coefficient λ_A

The previous study shows that the coefficient λ_A in (1) depends on the ratio of the pipe diameter to the water depth H, i.e. $\lambda_A=f(D/H)$ and can be estimated as (Yang *et al.* 2010):

$$\lambda_A = 13(D/H) + 5.3 \quad (9)$$

4.2.2 The bottom flow velocity u_b

The bottom flow velocity u_b in (1) is associated with the flow Reynolds number. Yang *et al*. (2010) showed that u_b can be estimated by:

$$\frac{u_b}{u_\infty} = -0.52\{\lg(\mathrm{Re})\}^2 + 4.32\lg(\mathrm{Re}) - 9.2 \quad (10)$$

where Re = the flow Reynolds number defined as $Re=u_{\infty *}D/v$ (where $u_{\infty *}$= the friction velocity at a point of the undisturbed upstream), The range of Re in this study is 11180 ~ 58140.

4.2.3 The coefficient m

The coefficient m in (2) is related to the pressure at the lee side of the pipe and therefore, depends on the flow condition. Jing (2007) showed that m is a function of the flow Reynolds number and can be evaluated by:

$$m = 2.274\{\lg(\mathrm{Re})\}^2 - 20.39\lg(\mathrm{Re}) + 44.42 \quad (11)$$

4.2.4 Determination of λ

The conservation of energy demonstrates that the kinetic energy of fluid partially converts into the pressure energy, indicating that the pressure difference Δp_{AB} depends on the incoming flow velocity u_∞ and the size of the pipe. As such, it is reasonable to assume that the coefficient λ in (5) is a function of the flow Reynolds number. Figure 6 is the plot of the experimental results from group A (Runs 05~13) in Table 1, showing the dependence of λ on the flow Reynolds number. The relationship can be expressed as:

$$\lambda = 0.39\lg(\mathrm{Re}) - 0.91 \quad (12)$$

4.2.5 Correction coefficient k

The coefficient k correlates the pressure difference between any two symmetrical points upstream and downstream about the pipe axis to the maximum pressure difference. Therefore, k depends on incoming flow velocity. Detailed analysis of the experimental data (Runs 01~ 07) shows that k is a function of the flow Froude number F_r ($Fr=u_\infty/(gH)^{0.5}$) which has the following relation (see Fig. 7):

$$k = 6.53Fr - 0.45 \tag{13}$$

4.3 Critical length of the rubber plate

The critical length is determined by the pressure difference of upstream and downstream of the pipeline which is mainly influenced by the flow velocity and the blocked area of the pipe. Therefore, it is reasonable to plot the critical length against the flow Reynolds number. Substituting the expressions of parameters into equation (8) yields the formula for estimating the critical length of the plate over which the scour below the pipeline will not take place. This formula is verified using two independent sets of experiments, namely group B and C in Table 1. The comparison between the experiments and calculated (using (8)) critical length of the plate is plotted in Fig. 8. In Fig. 8, close symbols are the experimental measurements while the open symbols are estimated from equation (8). It is seen that the critical length of the plate increases with the increase of the flow Reynolds number. This is reasonable as the higher Reynolds number represents either the higher flow velocity or larger size of the pipe or both, which will generate greater pressure difference, thus requires longer plate in order to prevent the sediment transport and scour around the pipeline. Fig. 8 also demonstrates that reasonable agreement between the calculated and experimentally determined critical length of the plate is obtained.

5. Conclusion

This paper investigates the critical pressure difference of sediment incipient motion, the pressure distribution on the seabed and the critical length of a rubber plate for the protection of the scour around the pipeline. The laboratory experiments show that a rubber plate place underneath the pipe can significantly reduce the pressure difference between upstream and downstream of the pipe. When the length of the rubber plate reaches a critical value for given flow conditions, there is no sediment transport and scour beneath the pipe. The formula for estimating such critical plate length is derived based on force balance acting on sediment particles. The formula is verified using the laboratory experiments and good agreement between the calculation and experiments is obtained for the input parameters investigated in this study.

The results presented in this study do not include waves which may apply an important role in practical marine situation and will need further investigation. Experiments with broad range of parameters (e.g. large ratio of the water depth to the pipe diameter) are desirable for the practical applications of this study.

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Notations: The following symbols are used in this paper:

C_L = the coefficient of uplift force, which is 0.178 (Chien and Wan, 1999);

D = the diameter of the pipe;

d = the mean diameter of sediment;

g = the gravitational acceleration;

h_f = the scour depth with a rubber plate;

h_0 = the scour depth without a plate;

k = a correction coefficient;

L = the length of plate;

m= a coefficient related to flow Reynolds number;

p_1= reference pressure at undisturbed upstream;

R_0 = radius of the pipe;

S = the specific gravity of sediment particles;

u_b = the bottom velocity of water on the seabed;

X = the horizontal distance on the bed which is symmetrical to the axis of the pipe;

y = the distance along the pipe surface from point B';

α = the angle defined in Fig.3 with the value of 0.22 radian in this study;

λ = a calibration coefficient.

λ_A = a calibration coefficient;

ρ = the specific weight of water;

ρ_s= the specific weight of sediment particles;

μ= correction coefficient;

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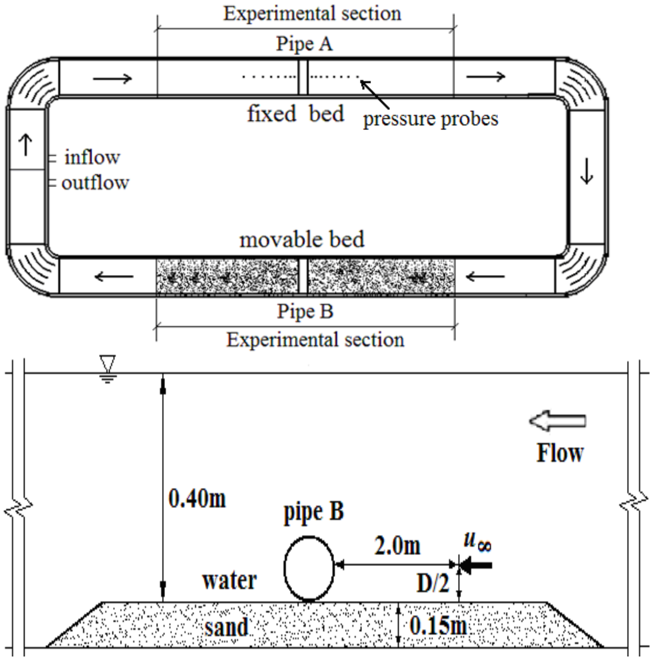

Fig.1 The flume experimental arrangement (a) the plane view; (b) the side view

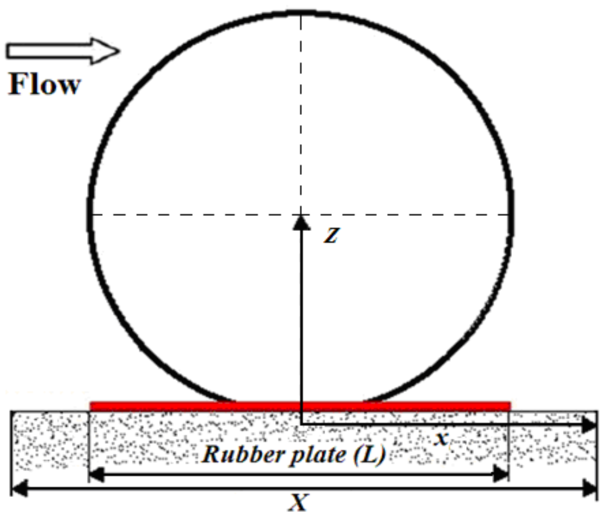

Fig.2 Rubber plate underneath the pipeline on sandy bed

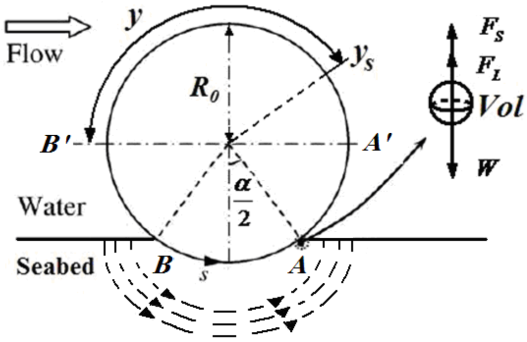

Fig.3 Sketch of seepage flow under the submarine pipeline (revised after Sumer et al. 2001)

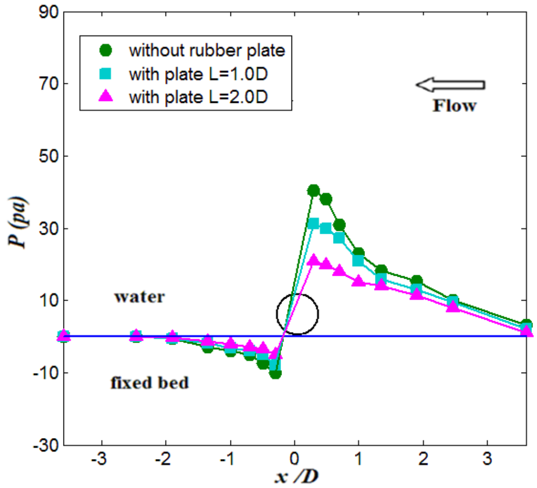

Fig.4 The pressure distribution on the bed for u∞=0.24m/s and D= 9cm with (length=1.0D and 2.0D) and without a plate

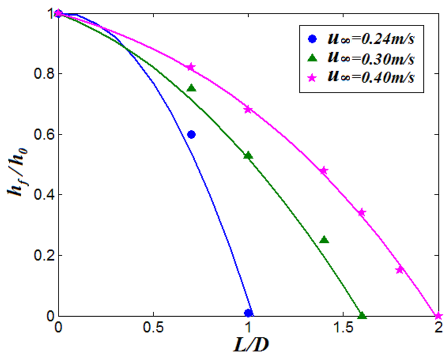

Fig.5 The effect of the plate length on the scour depth around the pipe for D=7cm and various incoming flow velocities

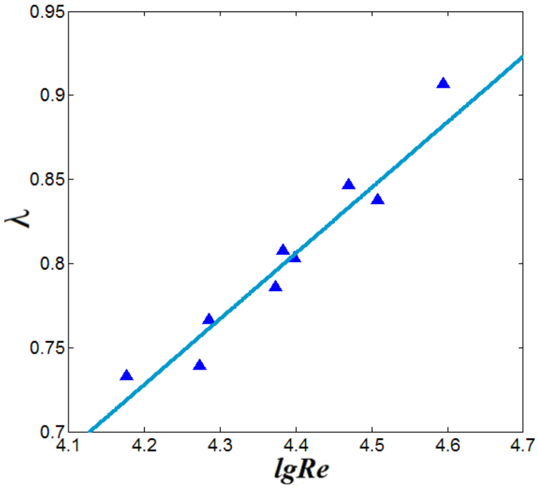

Fig. 6 The relation between coefficient λ and flow Reynolds number lgRe

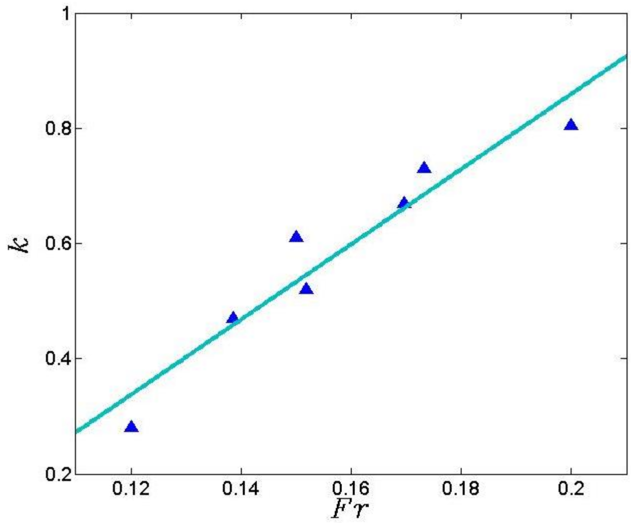

Fig. 7 The variation of coefficient k with flow Froude number Fr

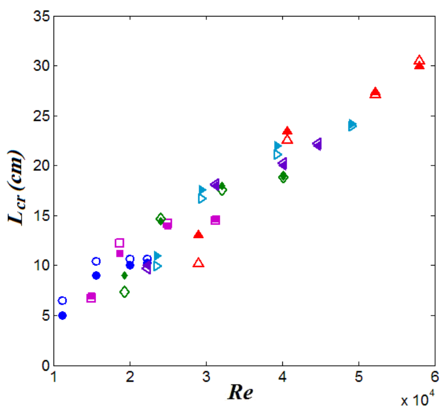

Fig.8. Comparison between the calculated and experimental values of Lcr. Symbols: experiments: ● D=5cm, ■ D=7cm, ◆ D=9cm, ◀ D=10cm, ▶ D=11cm, ▲ D=13cm for various incoming flow velocities; calculation using (8): the same symbols as experiments but open.

Table 1 Experimental parameters

Case	Runs	Pipe diameter D(cm)	Length of rubber plate	Velocity u_∞ (m/s)	Water Depth (m) H	Scour depth (cm)
	Run 01	7	0D	0.24	0.3	NS
	Run 02	7	0D	0.24	0.25	NS
	Run 03	9	0D	0.3	0.3	NS
	Run 04	11	0D	0.24	0.2	NS
	Run 05	9	0D	0.24	0.4	3
A	Run 06	9	0D	0.3	0.4	4.3
	Run 07	9	0D	0.4	0.4	6.2
	Run 08	7	0D	0.24	0.4	2.8
	Run 09	7	0D	0.3	0.4	3.7
	Run 10	7	0D	0.4	0.4	5.1
	Run 11	11	0D	0.24	0.4	3.4
	Run 12	11	0D	0.3	0.4	5
	Run 13	11	0D	0.4	0.4	7.1
	Run 14	7	0.7D,1.0D	0.24	0.4	1.7, 0
	Run 15	7	0.7D,1.0D,1.4D,1.6D	0.3	0.4	2.8, 2.0, 0.9, 0
	Run 16	7	0.7D,1.0D,1.4D,1.6D,1.8D,2.0D	0.4	0.4	4.2, 3.5, 2.4, 1.7, 0.7, 0
	Run 17	7	2.1D	0.5	0.4	0
	Run 18	9	0.7D,1.0D	0.24	0.4	1.5, 0
B	Run 19	9	0.7D,1.0D,1.4D,1.6D	0.3	0.4	2.6, 1.9, 0.8, 0
	Run 20	9	0.7D,1.0D,1.4D,1.6D,1.8D,2.0D	0.4	0.4	4.4, 3.6, 2.3, 1.5, 0.6, 0
	Run 21	9	2.1D	0.5	0.4	0
	Run 22	11	0.7D,1.0D	0.24	0.4	1.3, 0
	Run 23	11	0.7D,1.0D,1.4D,1.6D	0.3	0.4	2.5, 1.7, 0.7, 0
	Run 24	11	0.7D,1.0D,1.4D,1.6D,1.8D,2.0D	0.4	0.4	4.8, 3.7, 2.2, 1.3, 0.4, 0
	Run 25	11	2.2D	0.5	0.4	0
	Run 26	5	1.0D	0.25	0.4	0
	Run 27	5	1.8D	0.35	0.4	0
	Run 28	5	2.0D	0.45	0.4	0
	Run 29	5	2.05D	0.5	0.4	0
	Run 30	10	1.0D	0.25	0.4	0
	Run 31	10	1.8D	0.35	0.4	0
C	Run 32	10	2.0D	0.45	0.4	0
	Run 33	10	2.2D	0.5	0.4	0
	Run 34	13	1.0D	0.25	0.4	0
	Run 35	13	1.8D	0.35	0.4	0
	Run 36	13	2.1D	0.45	0.4	0
	Run 37	13	2.3D	0.5	0.4	0

Table 2 Mechanical properties of the plate material

Tensile strength	Yield strength	Total elongation	Elastic modulus	Percentage elongation	Fracture stress
Rm (N/mm^2)	Re (N/mm^2)	Agt(%)	E(Gpa)	A(%)	Rf (N/mm^2)
1.32	0.516	228.446	0.001	721.6	-0.073